The economic and geospatial viability of CO_2 capture and storage in shallow saline aquifers for geothermal energy generation in the Gulf Coast of the United States

Undergraduate Honors Research Thesis

Presented in Partial Fulfillment of the Requirements for

Graduation with Honors Research Distinction in the Civil, Environmental, and Geodetic Engineering Department of The Ohio State University

By

Dora de Melo

Undergraduate Program in Civil Engineering

The Ohio State University

2021

Dissertation Committee

Jeffrey Bielicki, Advisor

Daniel Gingerich

ABSTRACT

Carbon dioxide (CO_2) that has been geothermally heated due to emplacement in deep saline aquifers in sedimentary basins could be used to generate electricity. This CO_2-geothermal process is an extension of CO_2 Capture and Storage (CCS) that could simultaneously isolate CO_2 from the atmosphere and use it as a heat extraction fluid to produce geothermal energy. This approach may help to mitigate climate change by addressing two pressing problems for energy systems: (1) reducing CO_2 emissions from existing facilities, and (2) increasing the deployment and utilization of renewable energy technologies. Because the CO_2-geothermal process requires that CO_2 from point sources to be geologically stored and circulated in deep aquifers, it is necessary to understand how to transport CO_2 from the sources to the reservoirs. Assessing the integrated source-sink matching that considers the individual characteristics of each source and each potential reservoir is described as the viability of geologic storage capacity. This also provides the most comprehensive supply curve given economic and geospatial characteristics of the sources and reservoirs. In a case study of the South East United States, this project investigated the viability of CO_2-geothermal energy using the engineering-economic geospatial optimization approach, *SimCCS*. Findings from this study indicate that the chosen location is viable for storage of CO_2 and for CO_2-driven geothermal energy production. Additionally, incorporation of economic incentives demonstrates that the proposed CCS and CO_2-driven geothermal energy integrated systems is desirable and viable. This methodology developed herein can ultimately be used to determine whether the structure of current 45Q federal tax credit would incentivize using CO_2 strictly for storage or for geothermal energy production. Findings from this project could lead to the revision of policy change to more adequately incentivize storing CO_2 while simultaneously helping increase renewable energy on the grid.

Acknowledgments

I would like to express my deepest gratitude to Dr. Jeffrey Bielicki for his continued support. My undergraduate experience would not have been nearly as rewarding without your guidance. I would also like to thank Marcos Miranda and William Oyler for helping me throughout the entirety of this process. I truly appreciate your moral and professional support. I would like to thank all of the researchers across various institutions who made data collection and analysis possible. This project would not have happened without your time and dedication. Finally, I would like to thank you my family and friends for their endless encouragement – I would not have made it this far without you.

Portions of this study are based on work for a manuscript under preparation: De Melo, D., Oyler, W., Miranda, M., and Bielicki, J. "The Geospatial and Economic Viability of Using Geologically Stored CO_2 for Geothermal Electricity Generation in the United States." in preparation for the International Journal of Greenhouse Gas Control.

Vita

May 2017 ………………………….. Centennial High School

May 2021 ………………………….. B.S. Civil Engineering, The Ohio State University

Fields of Study

Major Field: Civil Engineering

Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction

Carbon dioxide (CO_2), which accounts for 65% of the global greenhouse gas emissions, is the primary greenhouse gas emitted through human activity. Since 1970, CO_2 emissions have increased by approximately 90%. In the United States alone, carbon emissions increased by approximately 2.9% from 1990-2017, with emissions in 2017 totaling 6,457 million metric tons of CO_2 equivalents[1]. Although CO_2 is naturally occurring, anthropogenic activities, such as combustion of fossil fuels, land-use changes, and industrial processes, have greatly increased the concentration of CO_2 in the atmosphere and in turn the effects of climate change[2].

One potential method to mitigate the negative effects of these emissions is to use CO_2 to produce geothermal energy, in which CO_2 could be diverted from the atmosphere and into appropriate reservoirs as part of a CO_2 capture and storage system (CCS). CCS is a process in which CO_2 is removed from exhaust streams of large emitters (e.g., coal or natural gas power plants) and compressed and transported into locations where it is injected into deep geologic formations to isolate it from the atmosphere with geologic CO_2 storage. CO_2 would be stored in deep, porous, and permeable saline aquifers, which are covered by low permeability caprock that acts as a physical barrier to impede to vertical movement of the buoyant CO_2. CCS can be used in conjunction with CO_2-driven geothermal energy, which extracts heat through naturally permeable sedimentary or stratigraphic basins. CO_2 stored in these geologic formations could be used as a geothermal working fluid because of its low kinematic viscosity, which allows for effective heat transfer. Because the density varies more with temperature than it does with brine, the need for pumps to circulate the fluid through the reservoir is reduced. Combining CO_2-driven geothermal energy with existing capture systems would create a carbon capture, utilization, and storage (CCUS) process, which would reduce costs of sequestration by reutilizing CO_2 as a resource for electricity generation[3]. Coupling CO_2-driven geothermal energy with CCS could increase renewable energy use at the expense of fossil fuel use. In addition, CCS would address CO_2 that is already being produced by existing facilities in the industrial and energy sectors, of which there are too many, by diverting emissions from going into atmosphere to geologic storage.

Previous projects have been done on the viability of CCS in hydrocarbon depleted fracture shale formations[3] and on the electric power output of CO_2-driven geothermal systems for varying reservoir conditions. However, there is no existing investigation of the viability of CO_2-driven geothermal on the integrated source – sink networks needed for geothermal energy generation to be viable. The results from this project will provide important information on supply curves, regional pipeline networks, the efficacy of the 45Q Federal Tax credit, and system-wide costs, capacities, and electricity production.

Chapter 2. Methods

A case study in the Gulf Coast region in the Southeast United States was conducted to assess the deployment of CO_2 storage and CO_2-driven geothermal power systems. The Gulf Coast represents a unique opportunity due to the abundance of sources of CO_2 available, as seen in Figure 1, and potentially favorable levelized cost of electricity (LCOE) values for CO_2-driven geothermal energy, which refers to the estimates of the revenue required to build and operate a generator over a specified cost recovery period[4]. There are also multiple oil fields in the region, some of which have been abandoned, and could serve as infrastructure for injection of CO_2, further supporting the deployment of CO_2-driven geothermal energy in the region.

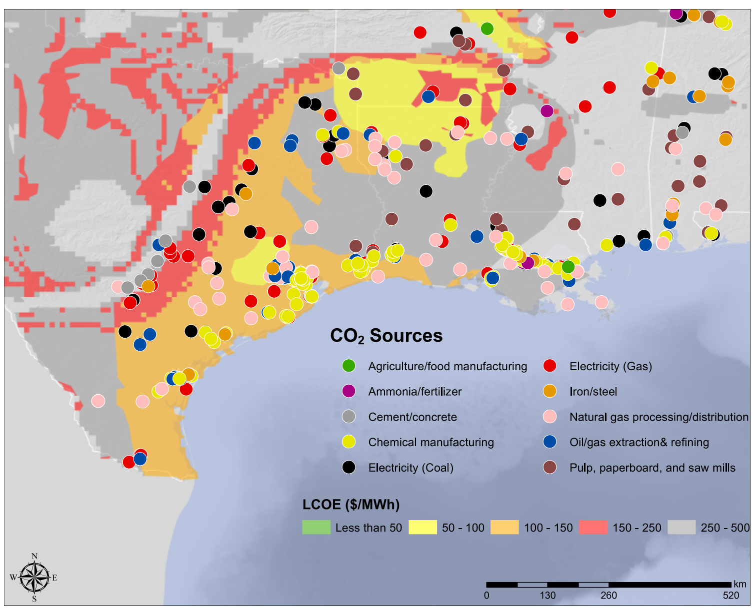

Figure 1: Locations, Types, and LCEO of CO_2 Sources in the Gulf Coast of the United States

To support this assessment, *SimCCS*, a fully integrated, holistic software package that considers sources, reservoirs, and transportation associated with CCUS was used[5]. *SimCCS* was used to design viable infrastructure networks that satisfied annual CO_2 capture targets (i.e., cost, capture capacity, and storage potential). A key component of the software is its ability to incorporate CO_2 storage costs, which are calculated using the Sequestration of CO_2 Tool (SCO2T). This CO_2 injection and storage model evaluates potential reservoirs and considers the economic aspects of sequestration engineering. SCO2T heeds the uncertainty and sensitivity of storage reservoirs by using inputs, such as formation depth, thickness, permeability, temperature, and porosity to calculate CO_2 storage costs. By incorporating SCO2T, viable projects can be prioritized based on the interaction between reservoir characteristics, infrastructure, and other constraints of a given storage region.

Data was organized in two scenarios: *saline* and *brownfield.* Saline scenarios only simulate CO_2 storage, while brownfield scenarios simulate geospatial deployment of CO_2-driven geothermal energy. Brownfield scenarios were created under the assumption that there is pre-existing infrastructure for injection of CO_2 at a chosen site and only the geothermal facility remains to be built.

It is important to note that *SimCCS* only takes inputs with units of dollars per ton of CO_2 ($/t$CO_2$). However, previously calculated costs were in dollars per megawatt hour ($/MWh). This inconsistency was mitigated using the conversion factors in Table 1. Additionally, the costs calculated using SCO2T for CO_2 storage were subtracted from the brownfield locations to avoid doubling the costs associated with construction, operation, and maintenance of CO_2 storage facility since it is assumed that such facilities already existed in these locations.

Table 1: Amount of CO_2 to Prime a 25 km^2 Footprint CPG System to Generate Electricity[6]

Geothermal Gradient (ºC/km)		20	35	50	20	35	50	20	35	50	20	35	50
CO_2 Required ($MtCO_2$)		232.7	173.3	125	236.5	182.6	140.3	262.2	186.9	148.7	242.8	189.9	153.3
Coal GW-years of CO_2		39.9	29.7	21.4	40.6	31.3	24.1	45	32	25.5	41.6	32	26.3
Natural Gas GW-years of CO_2		79.8	59.4	42.9	81.1	62.6	48.1	89.9	64.1	51	83.3	65.1	52.6
Electricity Generation ($MW/MtCO_2$)	$\kappa = 1x10^{-15}$												
	$\kappa = 5x10^{-15}$						0.2			2.31		0.33	0.87
	$\kappa = 1x10^{-14}$						0.37		0.25	0.69		0.62	1.66
	$\kappa = 5x10^{-14}$			0.55		0.37	1.63		2.41	3.14		5.68	3.05
	$\kappa = 1x10^{-13}$		0.44	0.61		0.48	1.66		0.97	2.7	0.29	1.93	4.64
	$\kappa = 1x10^{-12}$			0.64		0.63	2.08		1.19	3.29	0.37	2.27	5.5
	$\kappa = 1x10^{-11}$			0.64		0.67	2.21		1.26	3.46	0.37	2.31	5.57

2.1 Scenarios for Source – Sink Matching

SimCCS was used to develop candidate pipeline networks connecting locations of CO_2 sources to subsurface storage. The input data was organized based on rank ordered sets of sinks and sources, or scenarios. It was determined that desirable scenarios would consider the cheapest and largest capture and storage costs. Under this assumption, sources were grouped based on the cheapest CO_2 capture costs and the largest CO_2 emissions. Similarly, sinks were grouped based on the cheapest LCOEs and the largest CO_2 storage capacity. To accurately compare saline and brownfield results, each scenario had a counterpart of the opposing use. That is, a scenario with the largest *saline* sinks and largest sources was compared directly to a scenario with the largest *brownfield* sinks and largest sources. These scenarios are described in Table 1 and Table 2. The number of sources and sinks were chosen such that the CO_2 storage capacity in the reservoirs equaled or exceed the CO_2 emissions at each source. In this case study, the target CO_2 storage capacity was selected as 59.2 $MtCO_2$/year. It was found that the 40 cheapest and largest sources exceeded this threshold. Additionally, the 40 cheapest and largest saline sinks were also capable of storing this amount of CO_2. The cheapest brownfield sinks, however, did not meet this requirement and thus needed to be expanded. By increasing the number of sinks in this grouping to 53, a capture target of 61.3 $MtCO_2$/year was achieved, which was then comparable to the other sets. In this study, the *SimCCS* optimization model was run in increments of 5 $MtCO_2$/yr until the storage capacity goal was achieved.

Table 2: Description of Saline Sinks Storage Locations

		Saline Sinks Storage Locations	
		40 Cheapest	40 Largest
	CO_2 Storage Capacity ($MtCO_2$/yr)	59.2	59.2
Sources	**Total CO_2 Production ($MtCO_2$/yr)**		
40 Cheapest	80.6	*Economical Storage*	*Cheap Capture, High Storage*
40 Largest	175.6	*High Emissions Abatement, Cheap Storage*	*Most Emissions Abatement*

Table 3: Description of Brownfield Sinks Locations

		Brownfield Sinks Storage Locations	
		53 Cheapest	40 Largest
	CO_2 Storage Capacity ($MtCO_2$/yr)	61.3	59.2
Sources	**Total CO_2 Production ($MtCO_2$/yr)**		
40 Cheapest	80.6	*Economical Energy Production*	*Cheap Capture, High Energy Production*
40 Largest	175.6	*High Emissions Abatement, Cheap Energy*	*Most Energy Production*

2.2 Implementation of *SimCCS*

SimCCS uses a mixed integer programming (MILP) model to construct optimal CCS systems while minimizing total cost associated with it. This model was solved using CPLEX, a mixed integer optimizer. The total cost is a sum of both fixed and variable costs. Fixed costs include price to install capture technology, purchase land, construct pipelines, and build injection sites. Variable costs include capture costs, maintenance, operation, and pumping costs throughout the injection process[7]. To minimize the total cost, *SimCCS* considers several constraints, including costs, flow of CO_2 through the pipelines, CO_2 supply and storage capacity at each source and reservoirs, total target CO_2 capture amount, complete injection or transport out of a node, number of pipelines, and completion of construction. Additionally, *SimCCS* also considers a variety of inputs, including fixed cost for opening a source, constructing a pipeline, or opening a reservoir ($), variable cost for capturing CO_2 from a source, transport through a pipeline, or into a reservoir ($/ton), CO_2 capacity of a source node, pipeline, or reservoir (ton), target amount of CO_2 to be sequestered (ton), and a weighted cost surface[7]. The weighted cost surface includes the right of way and construction cost surface which consider the topography, crossings, ownership, land use, right of ways, and population at a specific location. Figure 2 below shows the variables included in each of these categories[8]. The constraint and input equations can be found in Figure B.1.

SimCCS produces optimal regional pipeline networks, from which supply curves can be generated by user specification of sources and sinks of CO_2[9]. Given a scenario, *SimCCS* generates a candidate network of potential networks and selects the optional path using the most attractive sinks and sources, which can be seen in Figure 3.

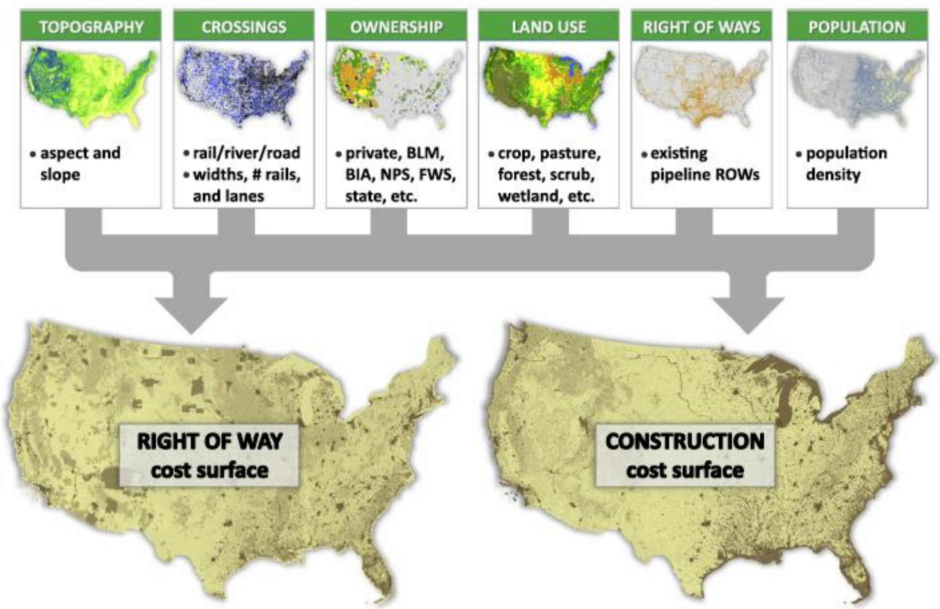

Figure 2: Cost Surface Considerations[8]

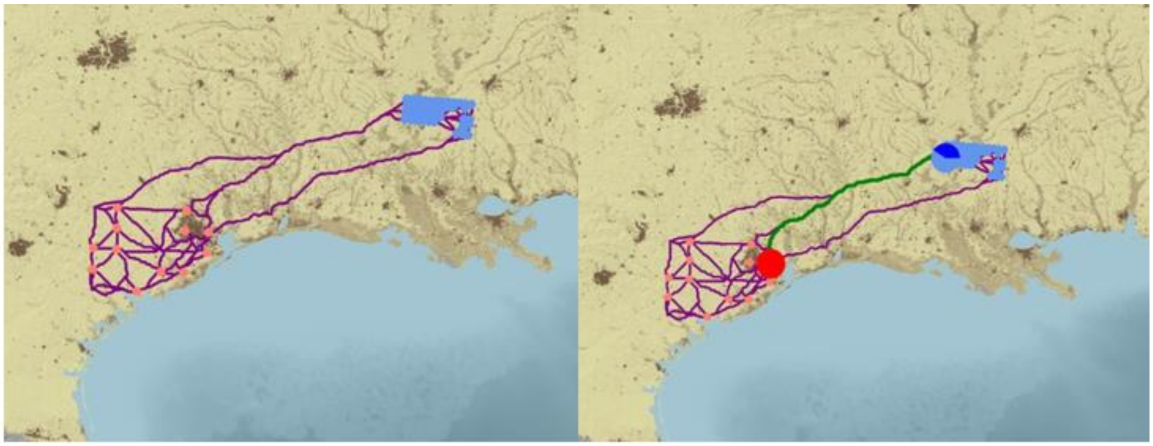

Figure 3: Candidate Network of Potential Routes for Pipelines (left) and Deployment of CO_2 Using Most Attractive Source (red) and Sinks (blue) (right)

2.3 26 U.S. Code 45Q

In addition to the geologic viability of employing CCS practices in the Gulf Coast, the economic viability was also explored. Although this tax code states several key provisions for CCS, this study focuses on its economic incentive to those who store and reutilize CO_2. The reforms made to the 45Q tax credit in 2018 increase the credit value to \$35 per metric ton of CO_2 stored geologically through enhanced oil recovery (EOR) and to \$50 per metric ton of CO_2 stored in geologic formations[10]. This was incorporated into the scenarios by subtracting \$35 per metric ton of CO_2 stored in *brownfield* sinks and \$50 per metric ton of CO_2 stored in *saline* sinks. The projected trajectory is that the tax credits will reach these values by 2026, which can be seen in Figure 4.

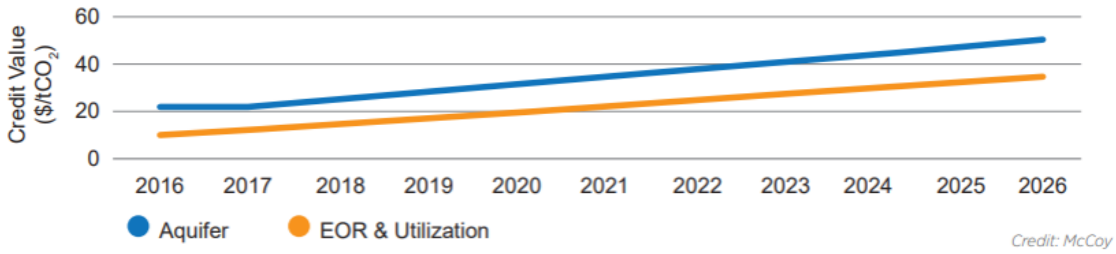

Figure 4: 45Q Types of Sources and Credit Between 2016-2026[10]

For the purpose of consistency and maximization, the full value of \$35 and \$50 per metric ton of CO_2 was utilized in this study. It was determined that the tax credit should be implemented into the *most emission abatement* and *most energy production* scenarios. These correspond to the largest sources and largest saline and brownfield sinks, which store the most CO_2 and thus maximize the total tax credit earned.

2.4 Electricity Generation

After subtracting the 45Q tax credits from the *most emission abatement* and *most energy production* total costs, the electricity generated as a function of the stored CO_2 was calculated using the following equation:

$$P = \frac{X \times C}{E \times G}$$

$$X = difference\ in\ total\ costs\ between\ scenarios(/MtCO_2)$$

$$C = capacityfactory(\%/year)$$

$$G = powergeneration(h/year)$$

$$E = price\ of\ electricity\ (\$/MWh)$$

$$P = electricity\ generated\ (MW/MtCO_2)$$

In this study, the capacity factor was held at 85% per year and the power generation was held at 8760 hours per year[11]. The electricity generated was calculated at each capture target in each scenario in intervals of 5 $MtCO_2$ per year until the desired storage capacity of 59.2 $MtCO_2$ per year was achieved. Based on the electricity production factors found in Table 1, it was determined that the desirable values were 1, 3, and 5 $MW/MtCO_2$. Therefore, the price of electricity was calculated in intervals of \$10/tCO_2 until electricity generation reached these values. The raw data for these calculations can be found in Table A.1.

Chapter 3. Results

The results from this study are two-fold: data including the 45Q tax credit were found and compared to data not including this incentive.

3.1 Comparison of Total Cost

Figure 5 below shows the total cost per ton of CO_2 for each scenario with and without the tax credit. The average total costs for each scenario across capture target intervals of 5 $MtCO_2$/year can be seen in Table 4. The absolute difference between the most emission abatement scenario with and without the tax incentive was found to be \$49.97/tCO_2, while that between the most energy production scenario with and without the tax incentive was found to be \$36.57/tCO_2. Additionally, the total cost per ton of CO_2 for the most energy production was on average \$5.26/tCO_2 more expensive than those of the most emission abatement scenario. The total cost per ton of CO_2 for the most energy production including the tax credit was on average \$18.66/tCO_2 more expensive than those of the most emission abatement scenario including the tax credit.

Table 4: Average Total Cost (\$/tCO_2) for each Scenario

	Most Energy Production	Most Emission Abatement	Most Energy Production - Tax Credit	Most Emission Abatement - Tax Credit
Average Total Cost (\$/tCO_2)	24.40	19.14	-12.17	-30.83

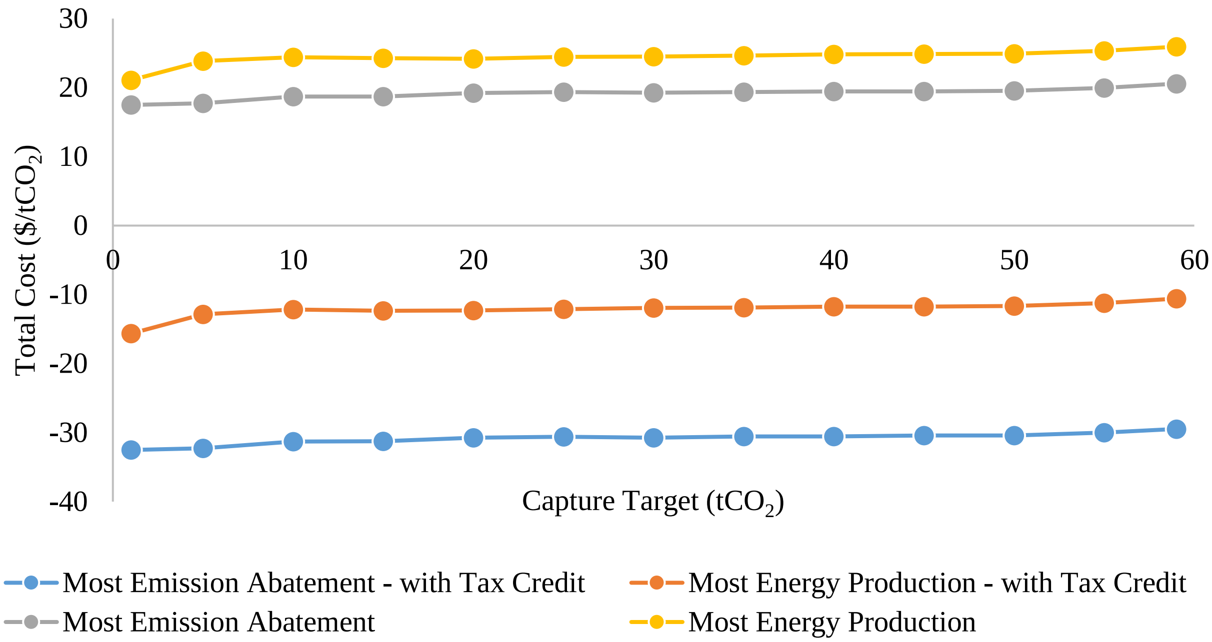

Figure 5: Total Cost ($/tCO_2$) for Most Emission Abatement and Most Energy Production Scenarios with and without 45Q Tax Credit

3.2 Price of Electricity

The electricity generation ($MW/MtCO_2$) was calculated for prices of electricity beginning at $70 until the desired values of 1, 3, and 5 $MW/MtCO_2$ were achieved. These calculations can be found in Appendix A. The average production of electricity across capture targets was plotted as a function of price of electricity, which can be seen in Figure 6.

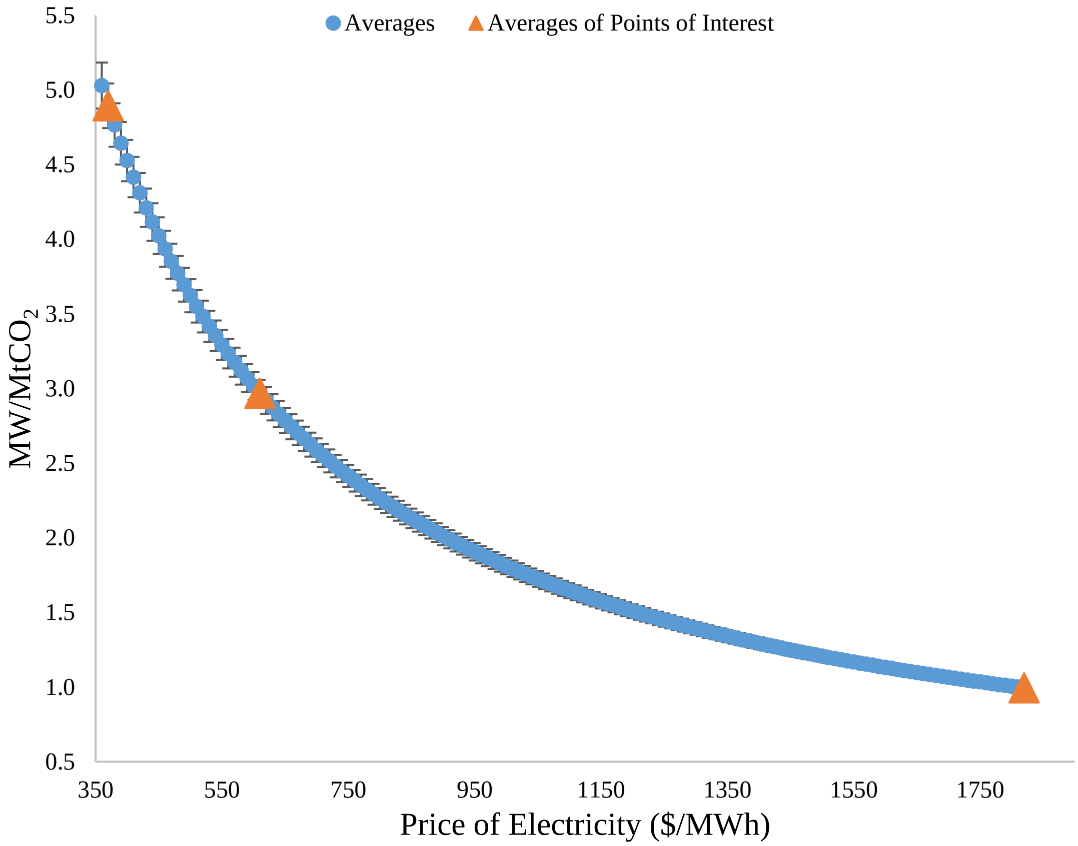

Figure 6:MW/MtCO$_2$ Produced as a Function of Price of Electricity

This graph shows the average MW/MtCO$_2$ produced given a price of electricity ranging from $350/MWh to $1900/MWh, highlighting the previously discussed points of interest. The error bars shown exist due to the range of costs associated with the capture targets in the chosen scenarios. Although this graph starts at $350/MWh in order to clearly show the desired production thresholds, it is important to note that this value is approximately 275% greater than the average residential price of electricity in the United States from January 2021, which was $126.9/MWh[12]. Based on this data, it was calculated that the average production of 1, 3, and 5 Mw/MtCO$_2$ was found at a price of $370, $610, and $1820/MWh.

Chapter 4. Discussion

The 45Q tax credit significantly subsidizes CCS costs in both saline and brownfield scenarios. Additionally, average production of electricity considering the 45Q tax credit decreases as price of electricity increases.

4.1 Cost Comparison

The comparison between costs based on scenarios shows that it is more cost effective to solely store CO_2 regardless of the tax credit. Based on the average prices prior to the subtraction of the tax credits, the most emission abatement storage was still cheaper than the most energy production scenarios. This indicates that if CCS were implemented in this location utilizing the largest sources and sinks, it would be more economically attractive to solely store CO_2. The difference in cost between the scenarios without considering the tax credit was much smaller than when tax credits were considered, indicating that the tax credit does provide economic incentive for storage and energy production.

4.2 Electricity Production

The average electricity productions were calculated based off the difference between total costs of the most emission abatement and most energy production scenarios. This indicates that the electricity production calculated at the points of interest represent the prices at which it would be economically attractive to transition from storage to electricity production. That is, at these price points, the difference in the 45Q tax credit for CO_2 used in EOR and CO_2 not used in EOR would no longer exist and either option would be just as viable based on the incentive. At the costs of $370, $610, and $1820/MWh, there would be no economic difference between storing and utilizing CO_2 for geothermal energy production. Although it is geologically viable to generate CO_2-driven geothermal energy, these prices of electricity are much higher than the average cost of electricity among all sectors (residential, commercial, industrial, transportation) in January 2021, which was $103.5/MWh. Based on this comparison, at current prices of electricity, it would not be economically viable to produce CO_2-driven geothermal energy for electricity generation. The LCOEs used in this model are unsubsidized costs, making them much higher than more established renewable energy costs. However, by 2050, it is predicted that over 90% of the subsidies to fossil fuels will be to support CCS in industrial applications, globally reaching $126 billion[13].This is a promising projection, as it would greatly decrease the cost of electricity associated with CO_2-driven geothermal energy production.

4.3 Implications of Work

As CO_2 concentration in the atmosphere continues to increase due to anthropogenic activity, it is crucial to engineer processes that can minimize these levels. This study investigates the viability of CO_2-driven geothermal energy to inform deployment potential and incorporation into national and global integrated assessment modeling efforts. Comparison of the total costs will indicate if production of electricity is recommended or if merely sequestration is more desirable. Furthermore, this project could have several implications of tax laws and policy regarding CO_2 sequestration and associated production of renewable energy. Specifically, data from this project can be used to assess the structure of the 45Q federal tax credit which could result in revision that more adequately incentivizes CO_2 storage while increasing use of renewable energy.

4.4 Limitation

This study examines the Gulf Coast in the Southeast of the United States. Results from this project indicate that the 45Q tax credit provides economic incentive for storage and energy production. However, these incentives are not sufficient to make the production of CO_2-driven geothermal energy viable at current prices of electricity for the specific geographic region analyzed. Further research needs to be conducted to determine if there are other areas in the United States that would be more attractive to consider for CO_2-driven geothermal energy. Additionally, the LCOEs considered in this report are unsubsidized, and thus not entirely representative of costs based on precedent of renewable energy subsidies. As subsidies change, an investigation should be conducted to determine how overall costs and attractiveness of CO_2-driven geothermal energy production are affected.

Chapter 5. Conclusion

Based on the results of this study, it is currently more economically attractive to store CO_2 in saline aquifers in the Gulf Coast rather than utilize it for CO_2-driven geothermal energy production, with or without 45Q tax credit incentives. This indicates that, given the current price of electricity needed to achieve a desirable energy production from captured CO_2, there is not enough incentive to reutilize CO_2 through EOR. This result could fluctuate in coming years as the price of electricity and subsidies for renewable energy evolve. Therefore, it is recommended that data be continuously analyzed to track these developments.

References

1. EPA. (2019b, September 13). Sources of Greenhouse Gas Emissions. Retrieved February 7, 2020, from https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

2. EPA. (2019a, April 11). Inventory of U.S. Greenhouse Gas Emissions and Sinks. Retrieved February 7, 2020, from https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

3. Adams, B. M., Kuehn, T. H., Bielicki, J. M., Randolph, J. B., & Saar, M. O. (2015). A comparison of electric power output of CO2 Plume Geothermal (CPG) and brine geothermal systems for varying reservoir conditions. *Applied Energy*, *140*, 365–377. https://doi.org/10.1016/j.apenergy.2014.11.043

4. U.S. Energy Information Administration. (2021, February). *Levelized Costs of New Generation Resources in the Annual Energy Outlook 2021*. https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf

5. Bielicki, J. M., Langenfeld, J. K., Tao, Z., Middleton, R. S., Menefee, A. H., & Clarens, A. F. (2018). The geospatial and economic viability of CO2 storage in hydrocarbon depleted fractured shale formations. International Journal of Greenhouse Gas Control, 75, 8–23. https://doi.org/10.1016/j.ijggc.2018.05.015

6. Bielicki, J. M, Adams, B. M, Miranda, M. M, Choi, H., Jamiyansuren, B, Taff, S. J, Buscheck, T. A, Ogland-Hand, J. D, Randolph, J. B, & Saar, M. O (in press). Cost-Competitive Geothermal Electricity from Geologic CO2 Storage.

7. Middleton, R. S., & Bielicki, J. M. (2009). A scalable infrastructure model for carbon capture and storage: SimCCS. *Energy Policy*, *37*(3), 1052–1060. https://doi.org/10.1016/j.enpol.2008.09.049

8. Richard S. Middleton, Michael J. Kuby, Jeffrey M. Bielicki, Generating candidate networks for optimization: The CO2 capture and storage optimization problem, Computers, Environment and Urban Systems, Volume 36, Issue 1, 2012, Pages 18-29, ISSN 0198-9715. https://doi.org/10.1016/j.compenvurbsys.2011.08.002.

9. Los Alamos National Laboratory, Operated by Los Alamos National Security, LLC, for the U.S. Department of Energy. (2019, November 6). Nine Los Alamos projects win R&D 100 Awards. Retrieved February 7, 2020, from https://www.lanl.gov/discover/news-releasearchive/2019/November/1106-rd-100-awards.ph

10. U.S. Department of Energy - Fossil Fuels. (2019, October). *Internal Revenue Code Tax Fact Sheet*. Fossil.Energy.Gov. https://www.energy.gov/sites/prod/files/2019/10/f67/Internal%20Revenue%20Code%20Tax%20Fact%20Sheet.pdf

11. National Renewable Energy Laboratory. (2010). *Simple Levelized Cost of Energy (LCOE) Calculator Documentation*. Energy Analysis | NREL. https://www.nrel.gov/analysis/tech-lcoe-documentation.html

12. U.S. Energy Information Administration. (2021a, January). *Electric Power Monthly - U.S. Energy Information Administration (EIA)*. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

13. Taylor, Michael (2020), Energy subsidies: Evolution in the global energy transformation to 2050, International Renewable Energy Agency, Abu Dhabi.

Appendix A. Raw Data

Table A 1: Average Energy Production (MW/MtCO_2) and Standard Deviation as a Function of Price of Electricity ($/MWh)

Price of Electricity ($/MWh)	Average Energy Production (MW/MtCO_2)	Standard Deviation
70	25.87	0.79
80	22.63	0.69
90	20.12	0.62
100	18.11	0.55
110	16.46	0.50
120	15.09	0.46
130	13.93	0.43
140	12.93	0.40
150	12.07	0.37
160	11.32	0.35
170	10.65	0.33
180	10.06	0.31
190	9.53	0.29
200	9.05	0.28
210	8.62	0.26
220	8.23	0.25
230	7.87	0.24
240	7.54	0.23
250	7.24	0.22
260	6.96	0.21
270	6.71	0.21
280	6.47	0.20
290	6.24	0.19
300	6.04	0.18
310	5.84	0.18
320	5.66	0.17
330	5.49	0.17
340	5.33	0.16
350	5.17	0.16
360	5.03	0.15
370	4.89	0.15
380	4.77	0.15
390	4.64	0.14
400	4.53	0.14
410	4.42	0.14
420	4.31	0.13
430	4.21	0.13
440	4.12	0.13
450	4.02	0.12
460	3.94	0.12

470	3.85	0.12
480	3.77	0.12
490	3.70	0.11
500	3.62	0.11
510	3.55	0.11
520	3.48	0.11
530	3.42	0.10
540	3.35	0.10
550	3.29	0.10
560	3.23	0.10
570	3.18	0.10
580	3.12	0.10
590	3.07	0.09
600	3.02	0.09
610	2.97	0.09
620	2.92	0.09
630	2.87	0.09
640	2.83	0.09
650	2.79	0.09
660	2.74	0.08
670	2.70	0.08
680	2.66	0.08
690	2.62	0.08
700	2.59	0.08
710	2.55	0.08
720	2.51	0.08
730	2.48	0.08
740	2.45	0.07
750	2.41	0.07
760	2.38	0.07
770	2.35	0.07
780	2.32	0.07
790	2.29	0.07
800	2.26	0.07
810	2.24	0.07
820	2.21	0.07
830	2.18	0.07
840	2.16	0.07
850	2.13	0.07
860	2.11	0.06
870	2.08	0.06
880	2.06	0.06
890	2.03	0.06
900	2.01	0.06
910	1.99	0.06
920	1.97	0.06

930	1.95	0.06
940	1.93	0.06
950	1.91	0.06
960	1.89	0.06
970	1.87	0.06
980	1.85	0.06
990	1.83	0.06
1000	1.81	0.06
1010	1.79	0.05
1020	1.78	0.05
1030	1.76	0.05
1040	1.74	0.05
1050	1.72	0.05
1060	1.71	0.05
1070	1.69	0.05
1080	1.68	0.05
1090	1.66	0.05
1100	1.65	0.05
1110	1.63	0.05
1120	1.62	0.05
1130	1.60	0.05
1140	1.59	0.05
1150	1.57	0.05
1160	1.56	0.05
1170	1.55	0.05
1180	1.53	0.05
1190	1.52	0.05
1200	1.51	0.05
1210	1.50	0.05
1220	1.48	0.05
1230	1.47	0.05
1240	1.46	0.04
1250	1.45	0.04
1260	1.44	0.04
1270	1.43	0.04
1280	1.41	0.04
1290	1.40	0.04
1300	1.39	0.04
1310	1.38	0.04
1320	1.37	0.04
1330	1.36	0.04
1340	1.35	0.04
1350	1.34	0.04
1360	1.33	0.04
1370	1.32	0.04
1380	1.31	0.04

1390	1.30	0.04
1400	1.29	0.04
1410	1.28	0.04
1420	1.28	0.04
1430	1.27	0.04
1440	1.26	0.04
1450	1.25	0.04
1460	1.24	0.04
1470	1.23	0.04
1480	1.22	0.04
1490	1.22	0.04
1500	1.21	0.04
1510	1.20	0.04
1520	1.19	0.04
1530	1.18	0.04
1540	1.18	0.04
1550	1.17	0.04
1560	1.16	0.04
1570	1.15	0.04
1580	1.15	0.04
1590	1.14	0.03
1600	1.13	0.03
1610	1.12	0.03
1620	1.12	0.03
1630	1.11	0.03
1640	1.10	0.03
1650	1.10	0.03
1660	1.09	0.03
1670	1.08	0.03
1680	1.08	0.03
1690	1.07	0.03
1700	1.07	0.03
1710	1.06	0.03
1720	1.05	0.03
1730	1.05	0.03
1740	1.04	0.03
1750	1.03	0.03
1760	1.03	0.03
1770	1.02	0.03
1780	1.02	0.03
1790	1.01	0.03
1800	1.01	0.03
1810	1.00	0.03
1820	0.99	0.03

Table A 2: Total Costs ($/tCO$_2$) for Most Emission Abatement and Most Energy Production Scenarios with and without 45Q Tax Credit

Capture Target (MT/yr)	Total Cost Most Energy Production ($/tCO$_2$)	Total Cost Most Emission Abatement ($/tCO$_2$)	Total Cost Most Energy Production with Tax Credit ($/tCO$_2$)	Total Cost Most Emission Abatement with Tax Credit ($/tCO$_2$)
1	21.07	17.48	-15.65	-32.52
5	23.82	17.72	-12.87	-32.28
10	24.41	18.71	-12.17	-31.29
15	24.25	18.71	-12.33	-31.27
20	24.19	19.23	-12.3	-30.74
25	24.43	19.35	-12.1	-30.59
30	24.51	19.27	-11.95	-30.72
35	24.63	19.36	-11.9	-30.57
40	24.82	19.43	-11.76	-30.54
45	24.88	19.45	-11.73	-30.43
50	24.91	19.54	-11.66	-30.41
55	25.33	19.94	-11.23	-30
59	25.92	20.57	-10.58	-29.47

Appendix B. *SimCCS* Constraints and Inputs

Cost to open source, capture CO_2 | Cost to purchase land, construct pipeline, and transport CO_2 | Cost to open reservoir, inject CO_2

Minimize

$$\sum_{i\in S}(F_i^s s_i + V_i^s a_i) + \sum_{i\in I}\sum_{j\in N_i}\sum_{d\in D} F_{ijd}^p y_{ijd} + \sum_{i\in I}\sum_{j\in N_i} V_{ij}^p x_{ij} + \sum_{j\in R}(F_j^r r_j + V_j^r b_j)$$

	Constraint	Domain	Description
(1)	$x_{ij} - \sum_{d\in D} {}_{\max}Q_{ijd}^p y_{ijd} \le 0$	$\forall i \in I, j \in N_i$	CO_2 flow must be less than maximum pipeline capacity
(2)	$x_{ij} - \sum_{d\in D} {}_{\min}Q_{ijd}^p y_{ijd} \ge 0$	$\forall i \in I, j \in N_i$	CO_2 flow must be more than minimum pipeline capacity
(3)	$\sum_{j\in N_i} x_{ij} - \sum_{j\in N_i} x_{ji} - a_i + b_i = 0$	$\forall i \in I$	CO_2 flow leaving a node must equal inflow
(4)	$a_i - Q_i^s s_i \le 0$	$\forall i \in S$	CO_2 stored at a source must not exceed supply
(5)	$b_j - Q_j^r r_j \le 0$	$\forall j \in R$	CO_2 stored at a sink must not exceed capacity
(6)	$\sum_{i\in S} a_i \ge T$		Target amount of CO_2 to store or sequester
(7)	$\sum_{d\in D} y_{ijd} \le 1$	$\forall i \in I, j \in N_i$	Only one pipeline can be built between nodes

$y_{ijd} \in \{0,1\}$ $\quad \forall i \in I, j \in N_i, d \in D$
$s_i \in \{0,1\}$ $\quad \forall i \in S$
$r_j \in \{0,1\}$ $\quad \forall j \in R$

0, 1 constraint

$x_{ij} \ge 0$ $\quad \forall i, j \in N_i$
$a_i \ge 0$ $\quad \forall j \in S$
$b_j \ge 0$ $\quad \forall j \in R$

Non-negative constraints

Figure A 1: *SimCCS* Inputs and Constraints[7]